

Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers Under Very High Wind Conditions

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LONG-TERM GOALS

The long-term goals are to contribute improvements in current physical understanding and modeling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and spray droplet production. These advances will improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe to extreme sea states.

OBJECTIVES

This project seeks to improve the reliability of air-sea interfacial flux parameterizations in coupled sea state/marine weather forecasting models, with a particular focus on refining and incorporating the role of wave breaking and sea spray in severe conditions. The approach adopted is to develop more realistic parameterizations for breaking occurrence and strength, and sea spray/spume source functions and validating them in test-bed models. The end goal is implementing these improvements in a coupled COAMPS/WaveWatch III model for operational use.

APPROACH

Our approach is to build substantially on our accumulated expertise in sea surface processes and air-sea interaction (Banner) and numerical weather modelling (Leslie) to identify and close fundamental knowledge gaps in order to improve the modeling accuracy for severe marine meteorological events such as hurricanes. Such improvements depend critically on gaining a more complete understanding of severe sea state phenomena linked to wave breaking, due to their increased surface drag and allied air-sea flux enhancements, including sea spray production.

Quantifying the distribution of wave breaking events has progressed substantially within this project as a result of an intensive collaboration with D. Farmer and J. Gemmrich (IOS, Canada) in FY01. From their storm wave datasets, a robust *threshold behavior* was identified for wave breaking at different scales in terms of the wave spectral saturation level $B(f)$ (Banner et al, 2002, hereafter BGF02). Here

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14. ABSTRACT The long-term goals are to contribute improvements in current physical understanding and modeling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and spray droplet production. These advances will improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe to extreme sea states.					
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$B(f)$ is given by $B(f) = (2\pi)^4 f^5 F(f) / 2g^2$, where $F(f)$ is the wave energy spectrum. This result has proven very useful in our ongoing effort to parameterize wave breaking spectrally in wind-wave models, and underpins our new spectral source term formulations for the wave energy dissipation rate. It is also being used in the spray/spume production term formulated in collaboration with C. Fairall (NOAA).

Model development in this project has focused on refining *full-bandwidth* computations of the directional wave spectrum and its tail region using ‘exact’ versions of the nonlinear wave-wave interaction source term in the radiative transfer equation for the wave field. We have concentrated on fetch-limited and duration-limited growth cases, since the bulk of observational data exists for these cases. This ensures that modeled spectral saturation levels (and dissipation rates) are consistent with observed levels, which is essential for predicting spectral breaking wave properties and reliable calculation of the enhanced air-sea fluxes associated with wave breaking. This is needed to underpin future operational versions of coupled atmosphere-wave-ocean models.

We have focused strongly on formulating, implementing and refining modeling strategies for: (a) extracting the relevant wave breaking parameters and (b) calculating wind stress/roughness length enhancements and updating the surface layer winds accordingly. For (a), we have significantly refined our previously reported capabilities for calculating the spectral density of mean breaking wave crest length/unit area. This is a primary goal of this project, as this quantity is central to the prediction of breaking wave enhancements to the wind stress, and development of a spray/spume source function based on sea state rather than the wind strength. Progress has been made by refining the form of S_{ds} proposed by Alves and Banner (2002) [hereafter AB02] and on advances in predicting wave breaking probabilities at different wave scales in BGF02. In particular, the AB02 form of S_{ds} was upgraded to incorporate the observed BGF02 breaking saturation threshold. Also, various refinements were introduced to its spectral distribution in order to provide a much better match to the wind input source function S_{in} at higher wavenumbers, and to recently published spectral wave breaking observations of the spectral density of breaking crest length/unit area. To progress, we have had to invest very considerable effort evaluating various versions of the ‘exact’ S_{nl} code, wind input source terms S_{in} , and propagation schemes in the radiative transfer evolution equation, in order to ensure accuracy and minimise computational instabilities that can develop at higher wavenumbers.

WORK COMPLETED

1. Wind-wave evolution modeling.

A. uncoupled study

During FY05 we continued our main effort on hurricane wind-wave model development, with explicit computation of wave breaking properties. Our capability for computing the directional wave spectrum was refined further, with particular emphasis on the directional spectral tail region out to high frequencies. Attention was focused on extending the wind speed from the commonly observed 7-14 m/s wind speed range out to 30 m/s and beyond. Direct comparisons of model results with observations were made against 1D transect wave spectra and the breaking crest length spectra of Melville and Matusov (2002, hereafter MM02) and Gemmrich (2005), as well as the directional spreading data of Hwang et al. (2000). For the very high wind speeds representative of hurricane winds, our aim was to achieve stable model behavior, especially in the spectral tail region.

In the ‘uncoupled’ modeling phase, the wind input source term S_{in} was based on a modified parameterisation of Yan (1987), which embodies the traditionally-observed growth rate dependences on wind parameters linear near the spectral peak and quadratic in the spectral tail. It also provides energy input to the wind from waves outrunning the wind. These computations also used a state-of-the-art version of the ‘exact’ nonlinear source term S_{nl} (D. Resio, private communication). Our spectral wave energy dissipation rate source term, S_{ds} , has a primary dependence on wave nonlinearity through its functional dependences on the spectral saturation. The uncoupled model performance was investigated by running the spectral wave evolution equation for duration and fetch-limited conditions, computing the spectrum over a wide bandwidth, typically out to several Hz.

Throughout these calculations, the results for integral wave spectral properties such as mean energy and peak frequency achieved a close correspondence with the observed evolution behavior in Kahma and Calkoen (1992), as shown in previous annual reports. We also obtained very close model agreement, both level and spectral slope, with the high wavenumber tail of the 1-D transect spectrum observed by MM02, also shown in previous annual reports. Lastly, modeled directional spreading properties compared very favorably with the data of Hwang et al. (2000) and the more recent high wind speed results from the recent GOTEX experiment (Melville/Friehe), in regard to both the bimodal shape at higher wavenumbers and the mean spreading width against wavenumber.

On this basis, we proceeded to make extensive calculations of the spectral density of breaking crest length per unit area, and how these breaking wave spectra change with wind speed and wave age. While awaiting CBLAST hurricane data from the SIO camera deployments, the field observational results of MM02 and Gemmrich (2005) in the 7-14 m/s wind speed regime have been used to validate our model results.

From the spectral evolution calculations, of particular importance is the spectral distribution of the dissipation rate S_{ds} . The precise link between S_{ds} and the spectral density of breaking crest length/unit area $\Lambda(c)$ is a current research topic of considerable complexity.

The assumption that wave breaking dissipation is localized spectrally is not well-established, i.e. that spectral dissipation at scale c (or k) is only associated with breaking waves of that scale. If localized spectral dissipation is assumed, following Phillips (1985), calculation of $\Lambda(c)$ follows from:

$$S_{ds}(c) = b(c^5/g) \Lambda(c) \quad (1)$$

The non-dimensional coefficient b reflects the strength of breaking, but its spectral dependence is not known (Melville, 1996) and needs to be assessed observationally. As there are no available direct measurements of spectral dissipation rate S_{ds} , the available field measurements of $\Lambda(c)$ of MM02 and Gemmrich (2005) can be used to investigate whether our S_{ds} model provides a self-consistent and robust formulation under the localized spectral dissipation assumption.

There are, however, several known *non-local* sources of dissipation, such as attenuation of short waves both by longer breaking waves and also through strong nonlinear interaction with non-breaking, steep longer waves. In strongly forced sea states typical of hurricanes, these spectrally non-local effects are likely to be significant. Our model development effort has been extended to include such effects. Recent progress is described below under ‘New Results’.

B. coupling wind profile and sea surface aerodynamic roughness changes

It is well-recognized that forecasting wind-waves involves strong coupling between the wind and wave fields, and that the growth of waves is accompanied by corresponding changes in the marine atmospheric boundary layer. Embodying the complex physics of this coupling is an essential part of progress in improved forecasting. To address this challenge, we have developed a Fortran code that allows the iterative computation of the wind stress and wave spectrum in response to changes due to wave drag, including breaking-induced contributions. Our approach is based on the calculation of wave breaking properties from the wave spectrum, the consequent enhanced wave drag and the adjustment of the aerodynamic roughness length z_0 in the assumed logarithmic mean velocity profile for the surface layer wind field. In turn, the wave spectrum is modified in response to the updated wind profile. This has been incorporated into our coupled test-bed model, and we have been investigating its performance in great detail over a wide range of wind speeds up to hurricane strength. An important underlying quantity is $\Lambda(c)$, and the available data is crucial in validating the breaking wave extraction algorithm in the model. Representative coupled model results are described below under ‘Results’.

2. Sea-state dependent spume/spray droplet source term

In collaboration with C. Fairall and W. Asher, an exploratory laboratory experiment was staged in 2003. The aim was to seek a dependence of spume droplet flux on breaking wave properties rather on the wind speed. This approach underpins a new model of spume droplet production in terms of the surface dissipation rate of breaking waves developed with C. Fairall. Droplet measurements were made in wind velocities in the range $U_{10} \sim 20\text{-}35$ m/s, with paddle-initiated wind waves with frequencies of 1.36 -1.6 Hz. Salinity was varied from 0 to 25 ppt. The surface properties were measured with a small directional array of wire impedance gages each sampled at over 2000 Hz. An analysis was undertaken to extract a consistent measure of ‘surface disturbance energy level’. The results suggest a fundamental link between the spray/spume flux and the strength of breaking events. These findings indicate extrapolation to oceanic scales is a potentially fruitful future challenge. A parametric model based on this approach has been developed for testing in full physics models. A manuscript describing both the observations and the model is nearing completion. More details were given in the FY04 report.

NEW RESULTS

Coupled model results for hurricane wind speeds (30 m/s)

Previous annual reports for this project show the excellent correspondence between modeled and observed evolution for the key integral and spectral tail region properties, based on our generic saturation-based form for S_{ds} and the wind input source term S_{in} due to Yan (1987). The exact form of the nonlinear spectral transfer term S_{nl} . These results were obtained at lower wind speeds (7-15 m/s) assuming no coupling with the overlying wind profile and were described in previous annual reports. Different wind input functions can be accommodated by adjusting the exponents of the saturation-dependent terms in S_{ds} .

In the uncoupled model phase, we also carried out complementary computations of $\Lambda(c)$, the spectral density of breaking crest length/unit area of sea surface, expressed as a function of the wave phase speed c . The spectral form of Λ was based on the local spectral breaking assumption using eqn (1)

above, and our calculations indicated that the main balance in the tail is between S_{in} and S_{ds} , with S_{nl} secondary. The wind speeds investigated were those (7.2 and 13.6 m/s) of the old wind sea observations of MM02. When scaled by the cube of the friction velocity, the model results reproduced well the close to cubic wind speed dependence observed by MM02, and the c^{-6} spectral dependence obtained with a constant value of the breaking strength coefficient b in (1) matched the theoretical predictions of Phillips (1985) for $\Lambda(c)$ in the equilibrium subrange towards the spectral peak.

For the coupled model, we used the latest available form of S_{in} from the Lake George study (Donelan et al., 2005). The model S_{in} is formulated using the wind at a height of one-tenth of the local wave length, $U(\lambda/10)$, rather than u_* , and includes an explicit computation, and updating, of the aerodynamic roughness length due to the enhanced wave-coherent component of the wind stress, as described in section 1B above.

We have also generalized the localized spectral breaking assumption used in our uncoupled study, and now seek to incorporate parametrically the dissipation due to additional known mechanisms. These include the removal of short wave energy by the cumulative effect of longer breaking waves (e.g. Banner et al, 1989), and also by strong nonlinear interaction with steep dominant waves (e.g. Phillips and Banner, 1974). The spectral distribution $\Lambda(c)$ is now calculated from the residual local dissipation due to breaking at scale c , after the non-local contributions to dissipation at that spectral scale have been subtracted. The following figures show the key data products from a duration-limited run where the wind speed at 200m was set to 35 m/s. As the spectrum evolves, the model calculates the changing surface layer winds, in response to the sea state, which in turn modifies the near-surface wind profile.

The following figures show key aspects of the wave field during the evolution. These include key wave breaking spectral properties, in addition to the familiar wave spectra. The final figure shows the evolution of the wind stress constituents – non-breaking wave form drag, additional breaking wave form drag, and viscous frictional drag.

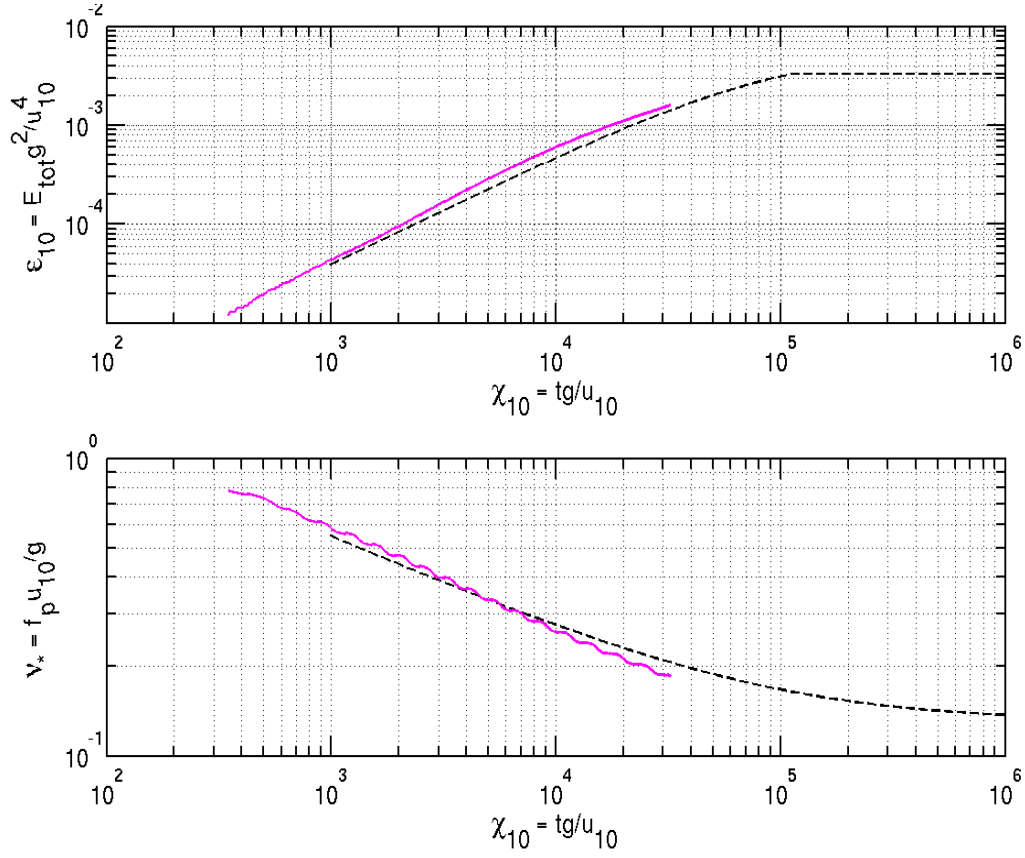


Figure 1. Evolution of the non-dimensional wave energy (upper panel) and non-dimensional dominant wave frequency (lower panel) against non-dimensional time. The background dashed curve is the trend of available field observations, gathered for lower wind speeds.

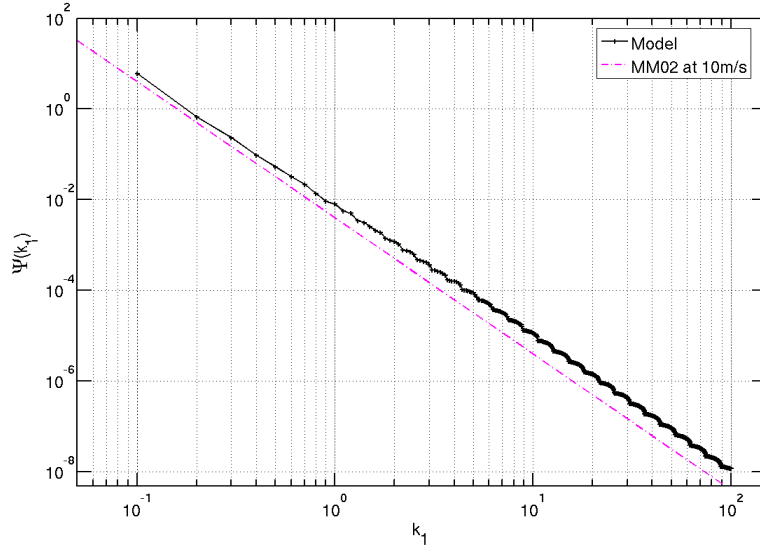


Figure 2. One-dimensional transect spectrum in the dominant wave (k_1) direction for mature seas, showing a k_1^{-3} behavior. The background curve was measured by MM02 for 7-13 m/s winds. The present tail spectral level, close to 3 times higher, indicates a near- linear dependence on wind speed.

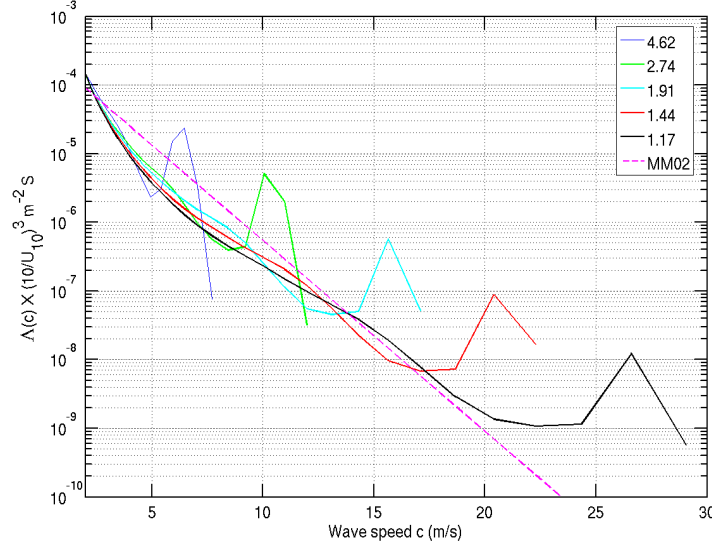


Figure 3. (a) azimuth-integrated spectral saturation against distance from the spectral peak wavenumber, for inverse wave age $U_{10}/c_p \sim 1.1$ (b) corresponding normalized saturation formed from (a) by division by the mean spreading width in radians (c) directional distribution of energy at different wavenumbers relative to the spectral peak (d) variation with wavenumber of the mean spreading width in degrees, compared with observations reported by Hwang et al. (2000). The calculations match the observed peaked off-wind nature and strong broadening of the direction spreading towards the shorter wave scales reported in recent field studies.

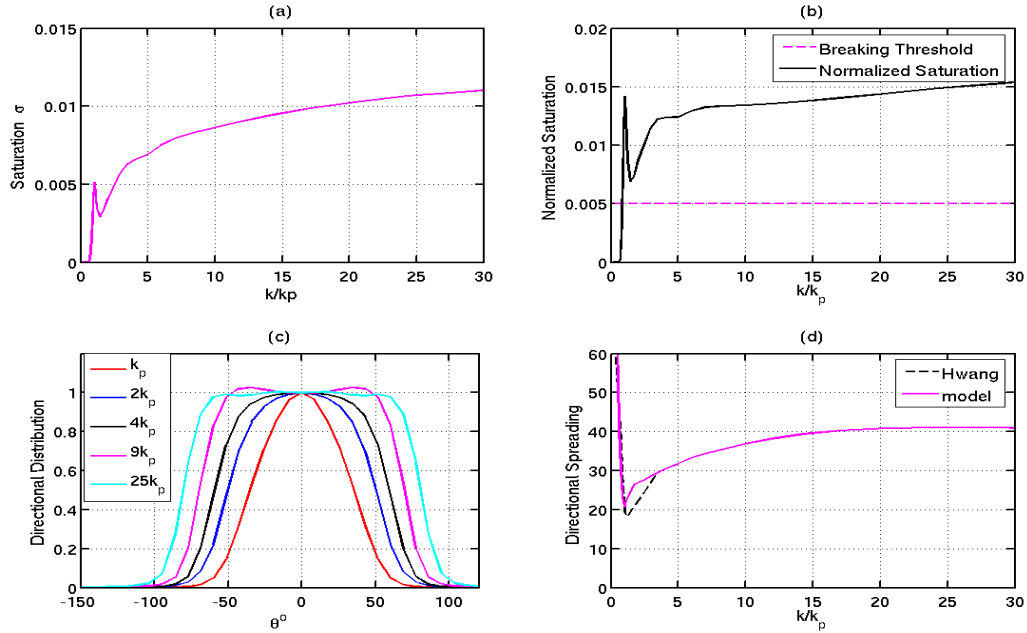


Figure 4. Evolution of the normalized spectral density of breaking crest length/unit area (Λ) against the wave speed. The legend shows the inverse wave age U_{10}/c_p . The normalization is based on U_{10}^3 , following MM02, and the dashed curve shows their data for lower wind speeds and fully developed seas. The enhanced Λ levels at the evolving spectral peak seen in these younger wind sea calculations tend to disappear towards full development.

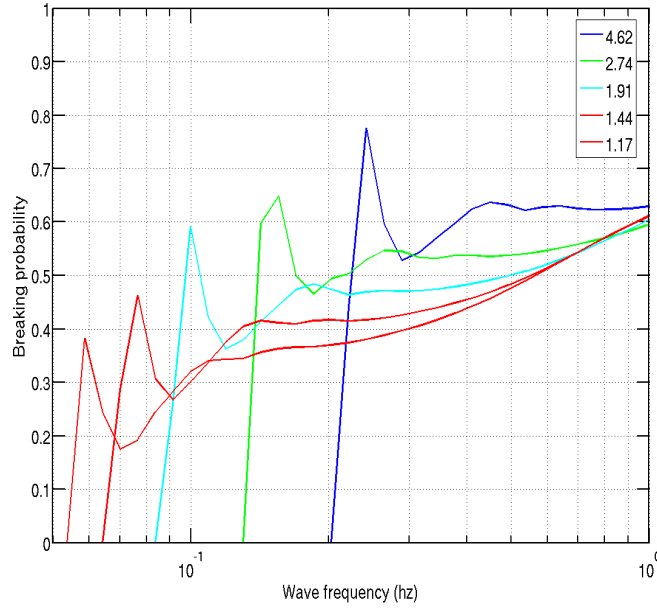


Figure 5. Evolution of the modeled distribution of breaking probability with wave frequency, based on a half-power extrapolation of the open ocean storm results of Banner et al. (2002) for winds up to gale force. The legend shows the inverse wave age U_{10}/c_p . Note the strong change in breaking probability as the sea ages at these high wind speeds, with significant levels of breaking probability forecast even when the seas are mature.

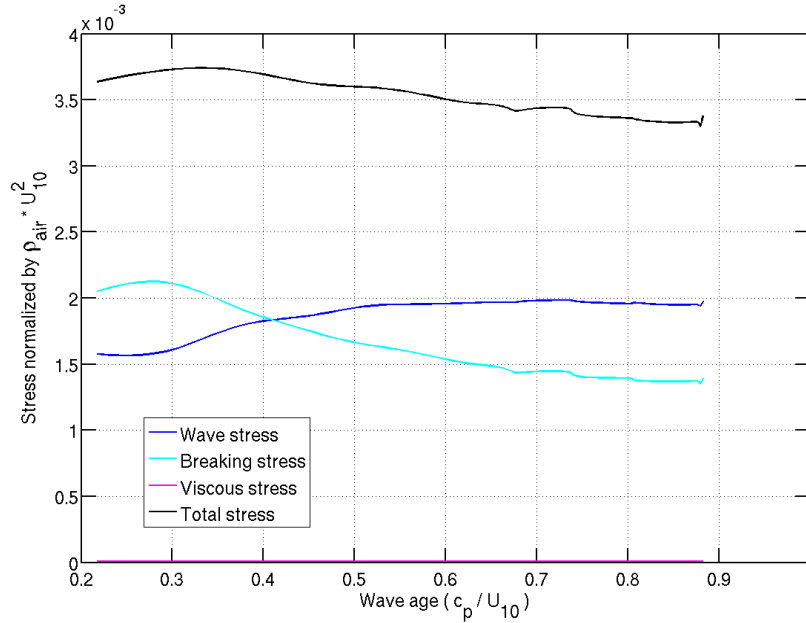


Figure 6. Evolution with wave age of the normalized wind stress (the sea surface drag coefficient). It decreases from about 0.0037 to 0.0033 as the wind sea ages. At full development, the projected value is around 0.0031. The normalized components of the wind stress are also shown, with the non-breaking wave stress increasing, while the breaking wave-induced stress decreases. The viscous stress level is insignificant for these near-hurricane winds.

Overall, these model results for near-hurricane wind speeds are very encouraging, but at this stage it is essential to perform model validations based on comparison with the CBLAST Hurricane project and other severe wind observation data sets, which are presently in progress. In the interim, further refinements of S_{ds} have been formulated and are being investigated.

IMPACT/APPLICATIONS

Enhanced scientific understanding of severe sea state air-sea interfacial processes, particularly wave breaking and spray/droplet production rates, will provide more reliable parameterizations of these processes and closely related air-sea fluxes when introduced into operational forecast models. These improved parameterizations will increase the reliability of operational sea state and marine meteorological forecasts, especially during severe marine weather conditions. Of particular benefit will be the capability to provide routine forecasts of occurrence rate of dangerous breaking waves.

RELATED PROJECTS

The ONR project *Source Term Balance for Finite Depth Wind Waves* (Young, Banner and Donelan) includes a strong focus on the influence of steep waves and wave breaking on the wind input source function in strongly forced, constant depth, shallow water environments. This data set has been analyzed and initial papers on the methodology and results have appeared in refereed journals, with other papers in preparation [e.g. Donelan et al, 2004; Banner et al., 2005]. In the present coupled modeling effort, we have implemented the form of wind input source function S_{in} from that project.

REFERENCES

- Alves, J.H.G.M. and Banner, M.L., 2002: Performance of a spectral saturation-based dissipation source term in modeling the fetch-limited evolution of wind-wave, *J. Phys. Oceanogr.* 33, 1274-1298.
- Banner, M.L., Gemmrich, J.R. and Farmer, D.M. 2002 Multiscale measurements of ocean wave breaking probability. *J. Phys. Oceanogr.*, 32, 3364-3375
- Gemmrich, J.G., 2005: 'On the occurrence of wave breaking', 14th 'Aha Huliko'a Hawaiian Winter Workshop, January 2005, Proceedings, to appear.
- Hwang, P.A., D.W. Wang, E.J. Walsh, W.B. Krabill & R.W. Swift, 2000: Airborne measurements of the wavenumber spectra of ocean surface waves. Part II: Directional distribution. *J. Phys. Oceanogr.*, 30, 2768-2787.
- Kahma, K.K. and Calkoen, 1992: Reconciling discrepancies in the observed growth of wind-generated waves. *J. Phys. Oceanogr.*, 22, 1389-1405.
- Melville, W.K., 1996: Energy dissipation by breaking waves. *J. Phys. Oceanogr.* 24, 2041-2049.
- Melville, W.K. and Matusov, P., 2002: Distribution of breaking waves at the ocean surface. *Nature* 417, 58-63.

Phillips, O.M., 1985: Spectral and statistical properties of the equilibrium range in wind-generated gravity waves. *J. Fluid Mech.*, 156, 505-531.

Yan, L., 1987: An improved wind input source term for third generation ocean wave modelling. Sci. Rept. WR-87-8, KNMI, De Bilt, the Netherlands, 10pp.

PUBLICATIONS

M. L. Banner

Babanin, A.V., Young, I.R and Banner, M.L. 2001 Breaking probabilities for dominant surface waves on water of finite constant depth. *J. Geophys. Res.* 106, C6, 11,659-11,676. [published, refereed]

Song, J. and Banner, M.L. 2002 On determining the onset and strength of breaking for deep water waves. Part 1: Unforced irrotational wave groups. *J. Phys. Oceanogr.* 32, 2541-2558. [published, refereed]

Banner, M.L. and Song, J. 2002 On determining the onset and strength of breaking for deep water waves. Part 2: Influence of wind forcing and surface shear. *J. Phys. Oceanogr.* 32, 2559-2570. [published, refereed]

Banner, M.L., J.R. Gemmrich and D.M. Farmer, 2002: Multiscale measurements of ocean wave breaking probability. *J. Phys. Oceanogr.* 32, 3364-3375. [published, refereed]

Alves, J.H., D.A. Greenslade and M.L. Banner, 2002: Impact of a saturation-dependent dissipation source term on wave hindcasts in the Australian region. *The Global Atmosphere and Ocean System*, 8, 239-267. [published, refereed]

Alves, J.H. and Banner, M.L. 2003: Performance of a spectral saturation-based dissipation source term in modeling the fetch-limited evolution of wind-wave. *J. Phys. Oceanogr.* 33, 1274-1298. [published, refereed]

Alves, J.H., Banner, M.L. and Young, I.R. 2003: Revisiting the asymptotic limits of fully developed seas. Part I: Reanalysis of the Pierson-Moskowitz database. *J. Phys. Oceanogr.*, 33, 1301-1323. [published, refereed]

Peirson, W.L. and M.L. Banner, 2003: Aqueous surface layer flows induced by micro-breaking wind waves. *J. Fluid Mech.* 479, 1-38. [published, refereed]

Donelan, M.A., A.V. Babanin, I.R. Young, M.L. Banner, and C. McCormick, 2004: Wave follower measurements of the wind input spectral function. Part I. Measurements and calibrations. *J. Atmos. Ocean Tech.*, 22, 7, 799-813. [published, refereed]

Young, I.R., M.L. Banner M.A., Donelan, A.V. Babanin, W.K. Melville, F. Veron and C. McCormick, 2004: An integrated system for the study of the wind wave source term balance in finite depth water. *Journal of Atmospheric and Ocean Technology*. [In press, refereed]

Donelan, M.A., A.V. Babanin, I.R. Young and M.L. Banner, 2003: The wind input source function for shallow water waves. Part 2.

Song, J. and M.L. Banner, 2004: On the influence of mean water depth and a subsurface sand bar on the onset and strength of wave breaking. *J. Phys. Oceanogr.*, 34, 950-960. [published, refereed]

M.L. Banner, A.V. Babanin, I.R. Young and Donelan, M.A., 2004: The wind input source function for shallow water waves. The wind input source function for shallow water waves. Part 3. Breaking wave enhancement.

I.R. Young, M.L. Banner M.A., Donelan, A.V. Babanin, W.K. Melville, F. Veron and C. McCormick, 2005: An integrated study of the wind wave source term balance in finite depth water. *J. Atmos. Ocean Tech.*, 22, 7, 814-828. [published, refereed]

L.M. Leslie:

PUBLICATIONS (2002-2005)

Book Chapters:

Leslie, LM, (2003): "High-resolution Atmospheric Modeling. Part I: Theory". Ch. 6 in "Impact Science." Eds. J. Nicholls and B. Pailthorpe. The Tandem Group Pty. Ltd., ISBN: 1 86487 551 8, 193pp. [published, refereed]

Leslie, LM, (2003): "High-resolution Atmospheric Modeling. Part II: Applications". Ch. 7 in "Impact Science." Eds. J. Nicholls and B. Pailthorpe. The Tandem Group Pty. Ltd., ISBN: 1 86487 551 8, 193pp. [published, refereed]

Leslie, LM (with G. Peng and Y. Shao), (2002): *Environmental Modeling and Prediction*, Springer, 480pp, ISBN 3-540-67422-5. [published, refereed]

Special Journal Issues:

Leslie, LM, DJ Karoly, PJ Lamb and L Qi, (2005): Special Issue on Regional Climate Variability and Change, Meteorology and Atmospherics, Springer Verlag, **89**, 267pp. [published, refereed]

Journal Publications:

Mo, X, K. Beven, S. Liu, LM Leslie and Ad PJ De Roo, (2005): Long term water budget estimation with the modified distributed model over the LUSHI basin, Part II, *Meteor. Atmos. Phys.*, **90**, 1-16. [published, refereed]

Leslie, LM, M. Leplastrier, BW Buckley and L Qi, (2005): Climatology of meteorological bombs in the New Zealand region, *Meteor. Atmos. Phys.*, **89**, 207-214. [published, refereed]

Mo, X, K. Beven, S. Liu, LM Leslie and Ad PJ De Roo, (2005): Long term water budget estimation with the modified distributed model LISFLOOD over the Lushi basin, China, *Meteor. Atmos. Phys.* **86**, 133-145. [published, refereed]

- Tan, KA, RP Morison, and LM Leslie, (2005): A comparison of high-order explicit and non-oscillatory finite difference advection schemes for climate and weather, *Meteor. Atmos. Phys.*, **89**, 251-267. [published, refereed]
- Mei Huang, Gongbing Peng, LM Leslie, Xuemei Shao and Wanying Sha, (2005): Seasonal and regional temperature changes in China over the 50 year period 1951-2000, *Meteor. Atmos. Phys.*, **89**, 105-115. [published, refereed]
- Leslie, LM, and MS Speer (2004): Preliminary modeling results of an urban air quality model verifying the prediction of nitrogen dioxide, sulfur dioxide and ozone over the Sydney basin. *Meteor. Atmos. Phys.* **87**, 89-93. [published, refereed]
- Buckley, BW and LM Leslie and MS Speer, (2004): Preliminary Climatology and Improved Modeling of South Indian Ocean and Southern Ocean Mid-Latitude Cyclones. *Int. J. Climatology* **24**, 1211-1230.
- Leslie, LM and L Xia, (2004): A GIS framework for the Traffic Emission Information System (TEIS). *Meteor. Atmos. Phys.* **87**, 153-160. [published, refereed]
- Speer, MS and LM Leslie, (2004): Preliminary Testing of an Urban Air Quality Model for Ozone Forecasting over the Sydney Basin, *Journal of the Korean Environmental Sciences Society*, **13**, 733-737. [published, refereed]
- Mo, X, K. Beven, S. Liu, LM Leslie and Ad PJ De Roo, (2004): Long term water budget estimation with the modified distributed model LISFLOOD over the Lushi basin, China, *Meteor. Atmos. Phys.* **86**, 133-145. [published, refereed]
- Le Marshall, JF, A Rea, LM Leslie, R Seecamp and M Dunn, (2004): Error characterization of atmospheric motion vectors. *Aust. Meteor. Mag.*, **53**, 123-131. [published, refereed]
- Speer, MS, LM Leslie and L Qi, (2004): Urban scale modeling: The Sydney hailstorm of 14 April 1999. *Meteor. Atmos. Phys.* **87**, 161-167. [published, refereed]
- Buckley, BW and LM Leslie and MS Speer, (2004): Preliminary Climatology and Improved Modelling of South Indian Ocean and Southern Ocean Mid-Latitude Cyclones. *Int. J. Climatology* **24**, 1211-1230. [published, refereed]
- Speer, MS and LM Leslie, (2004): Preliminary Testing of an Urban Air Quality Model for Ozone Forecasting over the Sydney Basin, *Journal of the Korean Environmental Sciences Society* [Accepted, In Press].
- Leslie, LM and MS Speer, (2003): Modeling a coastal ridging event over south-eastern Australia. *Meteor. Apps.* **10**, 293-294. [published, refereed]
- Y. Shao, LM. Leslie and 7 others, (2003): Northeast Asian dust storms: Real-time numerical prediction and validation. *J. Geophys. Res.*, Vol. 108, No. D22, 4691 DOI:10.1029/2003JD003667 (Online November 2003). [published, refereed]
- Liu, S, LM Leslie, MS Speer, R. Bunker, and X, Mo, (2003): The effects of bushfires on hydrological processes using a paired-catchment analysis, *Meteor. Atmos. Phys.* DOI:10.1007/s00703-003-0614-x (Online October 22, 2003). [published, refereed]

Buckley, BW and LM Leslie, (2003): The impact of observational technology on climate database quality. *J. Climate*, 16, 2640-2645. [published, refereed]

Leslie, LM, MS Speer and L. Qi, (2003): Prediction of Extreme Rainfall for the Coffs Harbour Catchment. *Aust. Meteor. Mag.*, 52, 95-100. [published, refereed]

Speer, MS, LM Leslie, and L. Qi, (2003): Numerical Prediction of Severe Convection: Comparison with Operational Forecasts, *Meteor. Apps.*, 10, 11-19. [published, refereed]

J. LeMarshall, JF, LM Leslie, R. Seecamp and A. Rea, (2003): Remote sensing applications in meteorology: A review, *MAUSAM*, 54, 1-12. [published, refereed]

Leslie, LM, JF LeMarshall and WL Smith, (2002): Mesoscale initialization using advanced sounder data, *Adv. Space Res.*, 30, 2479-2486. [published, refereed]

Shao, Y, E Jung and LM Leslie (2002): Numerical prediction of northeast Asian dust storms using an integrated wind erosion modeling system, *J. Geophys. Res.*, 107, 1493-1516. [published, refereed]

LeMarshall, JF, LM Leslie and WL Smith, (2002): Initialization of a NWP model using high spatial and temporal resolution satellite data, *Adv. Space Res.*, 30, 2441-2446. [published, refereed]

LeMarshall, JF, GA Mills, R. Seecamp, N. Pescod, LM Leslie and A. Rea, (2002): The estimation of high density atmospheric motion vectors and their application to operational NWP, *Australian Meteor. Mag.*, 51, 173-180. [published, refereed]

LeMarshall, JF, LM Leslie and RF Abbey (2002): Tropical cyclone track and intensity prediction: The generation and assimilation of high density satellite-derived data, *Meteor. Atmos. Phys.*, 80, 43-57. [published, refereed]

Leslie, LM, RF Abbey, MS Speer and TCL Skinner, (2002): Intense tropical cyclogenesis over the northwest Australian region in 1998/1999: Causal factors, *Meteor. Atmos. Phys.*, 80, 89-101. [published, refereed]

Morison, RP, Leslie, LM and MS Speer (2002): Atmospheric modeling of air pollution as a tool for environmental prediction and management, *Meteor. Atmos. Phys.*, 80, 141-151. [published, refereed]

Speer, MS, and LM Leslie (2002): The prediction of two cases of severe convection: implications for forecast guidance, *Meteor. Atmos. Phys.*, 80, 165-175. [published, refereed]

HONORS/AWARDS/PRIZES

Lance Leslie received one honor and one award in FY05. The honor was being elected as a Fellow of The American Meteorological Society. The award was a President's International Travel grant (PIT) to visit China as one of two US convenors of the inaugural US-China Symposia to be held every two years (alternating between the US and China) on some aspect of Atmospheric Science. One of his students (Brad Barrett) who is currently funded by this grant was awarded a Fulbright Scholarship.